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A Multichannel Architecture for Naval Task Force Communication

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13. ABSTRACT (Maximum 200 words) This report describes a new architecture for mobile, narrowband, broadcast radio networks, which is called the Multichannel Architecture (MCA). We compare the performance limits of an MCA network to a single-channel architecture based on an Ideal Handoff Assigned Multiple Access (IHAMA) protocol. Both architectures have been proposed for Naval intratask force communications with HF and line-of-sight UHF radio. Formulas for the network load capacity for each architecture are derived for several important cases, and simulation results are presented for those cases where analytical results are not available. Based on "equivalent" equipment, the load capacity of MCA is shown to exceed that of IHAMA. MCA also out-performed IHAMA in other performance areas such as delay, the ability to handle voice and virtual circuits, and jam resistance.				
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A MULTICHANNEL ARCHITECTURE FOR NAVAL TASK FORCE COMMUNICATION

1. INTRODUCTION

The present Naval intratask force communication system was deployed in 1959. Modern advances in weapons and sensor technology, and the advent of digital Command, Control, Communications, Computers, and Intelligence (C⁴I) systems have increased communication system requirements, resulting in recent efforts to improve or replace the existing Link-11 architecture. In addition to meeting the requirements imposed by the modernization of weapons systems, the replacement systems must face a more technologically advanced adversary. Modern communication jamming systems are a major threat to an intratask force communication system's integrity. To be able to capitalize on the advanced weapons systems and C⁴I systems, the communication system must also be able to respond to jamming effectively.

As in the case of Link-11, it can be expected that any communication system installed in the late 1990s will still be in use through the first quarter of the 21st century. Over this time period, communications requirements are likely to increase dramatically. Thus, the communication architecture should be designed for modular expansion to fit these future needs in a cost-effective fashion.

In this report, we describe one such system, the Multichannel Architecture (MCA) and compare its performance with the dominant single-channel approach, Handoff Assigned Multiple Access (HAMA). We show that the MCA is able to handle much larger loads and with much lower delays than comparably equipped HAMA systems. In addition, the ability to generalize the MCA to use arbitrary numbers of receivers provides a cost-effective path to system expansion.

The report is organized as follows. We complete Section 1 by examining the operational environment, describing the model of our concept of operation for an intratask force network, and providing definitions of the symbols and terms that we use. Section 2 describes three architectures that have been proposed for intratask force communications with high frequency (HF) and line-of-sight ultrahigh frequency (UHF) radio, namely, a single-channel architecture based on an Ideal HAMA (IHAMA) protocol, a multichannel architecture called the HF Intratask Force (ITF) Network, and a successor to the latter called the Multichannel Architecture. Formulas are derived for computing the network load capacity for IHAMA and MCA architectures for several important cases. Section 3 shows the results of the comparisons in chart form. Section 4 presents our conclusions.

1.1 Operational Environment

Before describing Ideal HAMA and MCA, it is important to characterize the intratask force communication environment. The environment is defined by several factors: topology, communications medium, and classes of service. All of these are important factors for consideration in the design of an intratask force network.

One of the more demanding aspects of designing an intratask force network architecture results from the continual relative motion of the communication platforms. This movement requires the system to adjust to changing communication topologies. The varying channel characteristics of HF and UHF communication can cause further topological change. These topological changes are intensified during an actual conflict. Under battle conditions, systems can experience equipment failure, node attrition, and jamming. To adjust to all of these factors, a communication system must be able to reorganize its assets quickly and use its new structure effectively. Thus, the reorganization technique must be rapid, robust, and efficient.

The choice of communication media is also an important factor in determining an effective networking strategy. For a variety of technical and operational reasons, HF and UHF broadcast links are used for intratask force communication. HF has the advantage of extended line of sight (ELOS) transmission at data rates on the order of 2400 bps. However, the range decreases with increasing frequency. UHF offers higher data rates (9600 bps), but is limited to line of sight (LOS) propagation. Due to the limitations of Link-11, current intratask force systems use the low end of the HF band to increase the likelihood of full connectivity. The structure of modern naval task forces and the limited range of 10 to 30 MHz HF and of UHF transmissions require message relaying when full connectivity is not provided. Relaying is not currently implemented in Link-11. By using modern networking concepts, the 10 to 30 MHz HF and UHF bands can be "opened up" for use in intratask force communication.

Every communication system is designed to support an application or set of applications. The communication needs of these applications, coupled with the topological factors described above, form the specification of the network. The requirements that intratask force applications impose upon the communication system can be broken down into several "classes of service." A class of service can be defined as a set of message delivery requirements imposed on a communication system by an application. Message types that differ significantly in timeliness, throughput, or reliability requirements need different protocols for delivery. In addition, different resources may need to be applied to achieve the class of service.

The traffic used in modern intratask force systems can be broken down into three general classes of service: target reports (Naval Tactical Data System (NTDS) data), computer-to-computer data, and voice. Each of these classes makes quite different requirements of the system. NTDS traffic has high-volume, low-delay requirements. In fact, if data is old, it can simply be replaced by more up-to-date data. Computer-to-computer data has greatly varying requirements. Downloading data, downloading code, and communication for distributed C⁴I systems are all potential uses of this class of service. One factor that is shared by computer-to-computer communication is the need for high reliability. The last class of service and perhaps the most difficult to implement is voice. Voice requires high bandwidth (1200 to 9600 bps), low delay (~1 s), and ordered delivery. Since HF channels are typically able to sustain only about 2400 bps, voice delivery requirements are very stressing for HF networks.

Quantitative communication requirements of future Naval intratask force networks are still not clear. But the need to implement the three classes of service mentioned and provide a path to future expansion to higher throughputs and lower delay is clear. Therefore, a network architecture that can implement the three classes of service and be easily and economically updated is needed. We believe that the Multichannel Architecture, which is described in this report, can fulfill this need.

1.2 Concept of Operation

To provide a basis for comparing alternative network architectures, we assume a simple communication model with a given communication range. This results in a network in which all connectivities are

bidirectional. Within this communication environment, each of the networks that we are examining share the same concept of operation, which we describe in this section.

The traffic model that we have chosen as our basis of comparison is one in which data traffic is uniformly generated by each of the network nodes, and this traffic is broadcast to all other nodes in the network. The mechanism for implementing this broadcast service is to organize a subset of the network nodes into a set of relays called the Backbone Network (BN). (In the Appendix, we discuss several techniques for establishing a backbone network.) Any valid set of relays must fulfill two criteria: 1) every node in the network must be connected to at least one relay and 2) the relays must form a connected subnet¹. In many cases, by minimizing the number of required relay nodes used for a network, the performance of the network can be optimized. A valid set of relays with the minimum number of relays is termed a Minimum Backbone Network (MBN).

Each relay is responsible for servicing the traffic entry for all of the neighboring nonrelay nodes and forwarding all other messages. In some cases, not all traffic must be relayed. We assume that sufficient information is available at a node that is receiving a transmission to ascertain whether the transmitting node is directly connected to all other nodes in the network.² When this is the case, the transmitting node is said to be “fully connected.” Thus, if the transmitting node is fully connected, its transmissions are not relayed. If all nodes in the network are fully connected, the network is said to be fully connected. If one or several (but not all) nodes are connected to all other nodes in the network, the network is said to be “star connected.” If none of the nodes are fully connected, we call the network a “multihop network.” In a multihop network, all traffic needs to be relayed. In our model, we assume that traffic that is relayed is transmitted by all relay nodes.

Once a backbone network is defined, transmission capacity is then allocated to each node in the network. This capacity is allocated in such a way that all relay nodes are given extra transmission capacity to handle relay traffic in addition to the traffic that they are generating (i.e., new traffic). Based on this operational model, we determine the limit of the traffic the network can generate (i.e., the load capacity of the network).

1.3 Definitions

We define the following symbols.

B	Number of relay nodes in the backbone network.
C	Maximum information rate obtainable from a single transmitter.
C_r	The part of a transmitter's capacity that is used for relay traffic.
D	Network dispersion: In our simulation model of networks, nodes are randomly positioned within a square whose sides are of length D .
F	Number of frequencies available for use by MCA.
$F_{i,j}$	Probability that node j has a receiver tuned to node i .

1. Assuming, of course, that the original network is connected.

2. An example of a protocol for learning local connectivities in a broadcast radio network is given in Ref. 1.

h_{\max}	Maximum value of X_j for the entire network.
k	Number of fully connected nodes.
L	Load: The load on the entire network: $L = Nl$
L_{\max}	Load capacity: The maximum load that can be sustained by the network: $L_{\max} = Nl_{\max}$.
L'_{\max}	Normalized load capacity: $L'_{\max} \equiv L_{\max}/C$, where “ \equiv ” means “is defined as.”
L''_{\max}	Equipment-normalized load capacity (ENLC): This is defined as L'_{\max} divided by the number of transmit and receive strings per node. For example, if there are one transmitter and one receiver per node, then the divisor is 2. On the other hand, if there are one transmitter and five receivers per node, the divisor is 6.
l	Load per node: This is the amount of new traffic that is generated by each node. To simplify the task of comparing alternative network architectures, we assume a uniform load per node.
l_{\max}	Load capacity per node: This is the maximum amount of new traffic that can be generated by each node.
N	Number of nodes in the network.
n_r	Number of receivers per node.
P_j	Percentage of traffic sourced by node j .
T_P	Packet transmission duration.
X_j	Number of relay nodes connected to node j .
ρ	Communication Range.
ρ'	Normalized Communication Range: $\rho' \equiv \rho/D$. See Fig. 1 and the accompanying caption.

2. ALTERNATIVE ARCHITECTURES FOR INTRATASK FORCE NETWORKS

2.1 A Fixed Time Division Multiple Access Approach

A simple approach to handling relaying in networks is to operate on a single-frequency, Fixed Time Division Multiple Access (FTDMA) schedule. In a FTDMA system, each node in the network is assigned a time slot in a schedule in which it can transmit. These time slots are assigned so that no two transmitters operate at the same time. By scheduling in this fashion, there is no chance of a transmission scheduling conflict, i.e., two transmitters scheduled at the same time at the same frequency. However, the FTDMA is inefficient for systems with uneven traffic creation rates or relaying. For a multihop network that uses FTDMA, the entire traffic load must pass through each relay node. Since the maximum allowed transmission rate per node in an FTDMA network is C/N (irrespective of whether or not a node is a relay), the maximum load (i.e., load capacity) that the network can sustain is given by

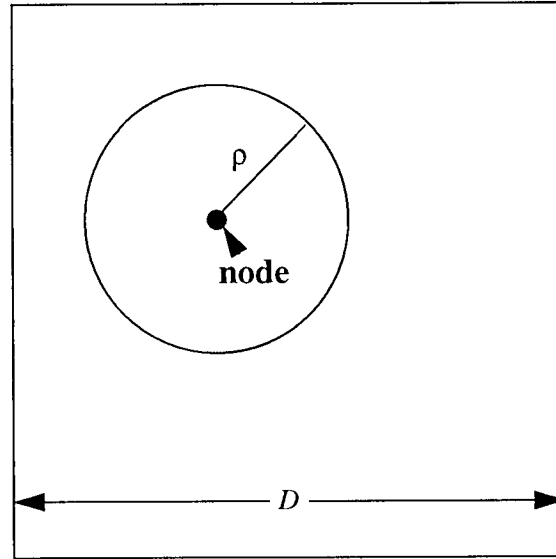


Fig. 1 — Definition of the Normalized Communication Range ρ' . In our simulation model, nodes are positioned randomly in a square region of width D . All nodes within communication range ρ are connected to each other. The Normalized Communication Range is defined as the ratio $\rho' = \rho / D$.

$$L_{\max} = C/N \quad (\text{multihop FTDMA network})$$

or, in terms of the normalized load capacity,

$$L'_{\max} = 1/N \quad (\text{multihop FTDMA network}).$$

Therefore the load capacity varies inversely with the network size.

2.2 Ideal Handoff Assigned Multiple Access Approach

A modification of FTDMA can be made to allow unequal amounts of transmission time at each node. However, if the system is dynamic, a protocol must be established that allocates capacity to nodes according to their requirements. One method of doing this in a distributed way is to have nodes “hand off” a portion of their capacity to a neighbor. This technique is known as Handoff Assigned Multiple Access (HAMA) [2, 3]. After capacity handoff is complete, the system operates in a fashion similar to FTDMA, except that some nodes get more slots than others.

Figure 2 shows a sequence of slot reallocations that occur in an Ideal HAMA (IHAMA) system for a simple network. The example eight-node network requires that three nodes (solid-filled circles) act as relay nodes. Initially (panel (a)), each node is allocated 100 minislots per frame. The example assumes that each node computes the ideal capacity allocation, shown in panel (c). For the example topology, the ideal capacity allocation is achieved in two steps. In the first step (panel (b)), nonrelay nodes forward unneeded capacity to neighboring relay nodes. In the second step (panel (c)), capacity is distributed uniformly to all relay nodes.

When examining the optimal behavior of an IHAMA system, one can assume the capability for permanent slot handoff and very many slots per node per frame. This IHAMA gives an upper bound to the

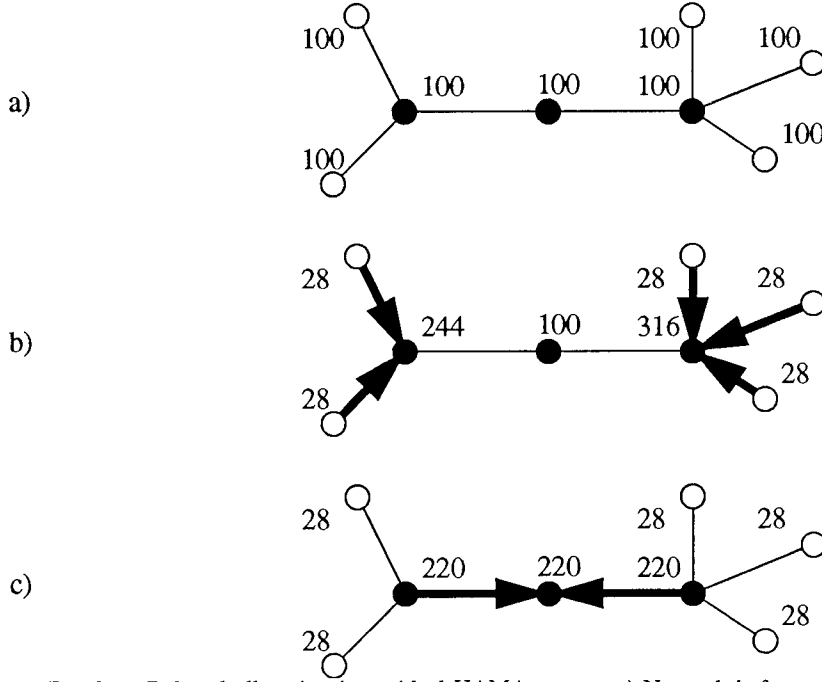


Fig. 2 — Relayed allocation in an ideal HAMA system. a) Network before capacity assignment has 100 minislots per node. b) Nonrelay nodes forward all unneeded capacity to neighboring nodes. c) Final capacity allocation takes place.

performance of a real HAMA system. To see what kind of throughput an N -node, IHAMA system can achieve, we can divide the system transmission capacity into relay capacity and new traffic generation capacity. For this analysis, all platforms are assumed to generate new traffic at the same rate l . (The results are only slightly affected by a nonuniform traffic generation.) For broadcast traffic and a multihop network, we can assume that each of the B relay nodes needs to relay all of the traffic except the traffic it creates: $C_r = (N-1)l$. Thus, the total transmission capacity used by the system is $B(N-1)l + Nl$. In the IHAMA system, all transmitters share access to a single, common channel. Therefore, the system capacity is equivalent to the transmission capacity C of a single node that is allowed to transmit all of the time. Thus, the load capacity per node for an IHAMA network can be obtained from the equation $B(N-1)l_{\max} + Nl_{\max} = C$, and the load capacity of the entire network is

$$L_{\max} = Nl_{\max} = C / (B + 1 - B/N) \approx C / (B + 1) \quad (\text{multihop IHAMA network}).$$

The equations become more complex if the nodes have differing traffic generation capacities. In either case, the more relay nodes used, the lower the load capacity of the system. Thus, the load capacity varies, approximately, with the number of relay nodes required.

The situation is a little different for star-connected IHAMA networks. We let k denote the number of fully connected nodes in the network. The transmission capacity is divided into relay traffic $(N-k)l$ and nonrelay traffic Nl . Equating this traffic level to the total transmission capacity C of the system, we can solve for the load capacity per node. This leads us to the following expression for the normalized load capacity.

$$L'_{\max} = 1 / (2 - k/N) \quad (\text{IHAMA network with } k \text{ fully connected nodes}).$$

Here, $1 \leq k \leq N$. Thus, for an IHAMA network with only one node that is fully connected, $L'_{\max} \approx 1/2$.

For fully connected IHAMA networks, no relaying is necessary. In that case, the load capacity is limited by the need for all nodes to share a single channel of capacity C . Therefore, for this case we have

$$L'_{\max} = 1 \quad (\text{fully connected IHAMA network}).$$

2.3 HF ITF Network Approach

Another intratask force networking concept is the HF ITF Network [4, 5]. This network is developed around a network structure known as the Linked Cluster Architecture (LCA)[1, 6]. The HF ITF Network uses a distributed protocol called the Linked Cluster Algorithm to set up and maintain the Linked Cluster structure. Figure 3 shows the nomenclature for describing the LCA. Nodes are assigned one of the following labels in this architecture: clusterhead, gateway, or ordinary. For simplicity, the example is for the case of a fixed communication range model — the communication range of each clusterhead is shown by the radius of the surrounding circle. With this simple model, clusters can be easily identified. A cluster consists of a set of nodes that are bidirectionally linked to a common clusterhead node. A node can be connected to several clusterheads, depending on the topology. However, because of the way clusterheads are selected, they are never directly connected. This tends to spread out the clusters. An isolated clusterhead is a cluster with only one member, i.e., itself. Every node is either a clusterhead or is bidirectionally connected to a clusterhead. An adjacent pair of clusterheads can be linked either by a single relay (adjacent, overlapping clusters) or by two relay nodes (adjacent, non-overlapping cases). Figure 3 shows both cases. If several nodes can act as relays to link adjacent clusterheads, the Linked Cluster Algorithm designates a preferred relay (adjacent overlapping clusters) or relay pair (adjacent non-overlapping clusters). Such a node is called a gateway. Nodes that are neither clusterheads nor gateway nodes are referred to as ordinary nodes.

In the HF ITF Network, the LCA is used to facilitate the routing of traffic and to allocate channel capacity. The HF ITF Network is a multichannel network, which can be implemented with either narrowband or spread spectrum channels. For the case of narrowband channels, which is the focus of this report, each node is assigned a unique transmit frequency. This allows several nodes to transmit simultaneously without interfering. However, to take advantage of multiple, simultaneous transmissions, several receivers (approximately five) are needed for each platform. The transmission slot allocations are determined by the clusterheads. Each clusterhead produces a Cluster Transmission Schedule for those nodes within its cluster. The result is a transmission schedule for every cluster plus an additional FTDMA schedule, which operates in parallel with the Cluster Transmission Schedules [4].

As networks become sparse (dispersed relative to the communication range) the number of relays grows, reducing IHAMA performance. However, since sparse networks result in more clusters in the LCA, the extra transmission capacity of the additional Cluster Transmission Schedules tends to compensate for the increased number of relays. This is in contrast to IHAMA whose load capacity decreases with an increasing number of relays and FTDMA whose load capacity decreases with an increasing number of nodes. The HF ITF Network requires several (approximately five) receivers per node to accomplish this. However, if high load capacity is required, the HF ITF Network provides this capacity more cheaply than do IHAMA architectures since it is achieved with added receivers, not added transmitter-receiver pairs.

2.4 Multichannel Architecture (MCA)

The MCA is a logical development from the concepts first introduced with the LCA and later brought to fruition in the HF ITF Network. Like the HF ITF Network, it uses multiple frequencies and periodic structural reorganization to enhance its load capacity and reliability. However, several significant changes

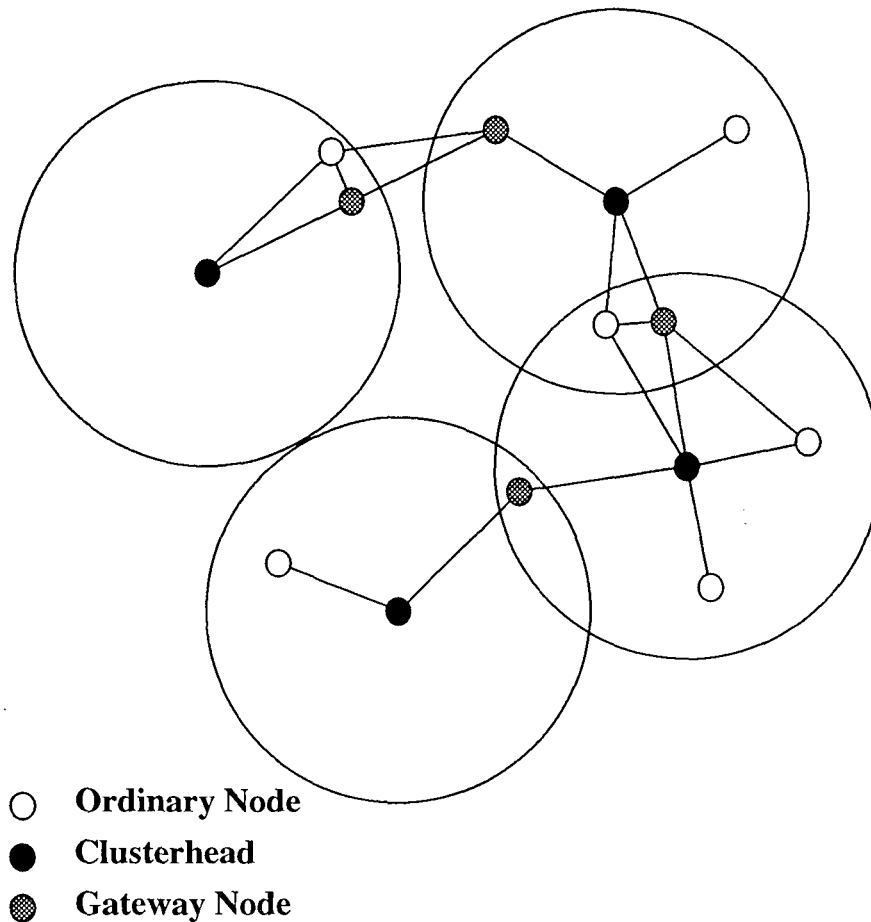


Fig. 3 — The Linked Cluster Architecture

in the methodology used for transmitter and receiver scheduling as well as the generalization of LCA for arbitrary transmission, reception, and frequency resources warrant a different name for the architecture.

The HF ITF Network's transmission capacity is limited by the number of clusters, and each node requires several receivers. Further studies of the HF ITF Network [7,8] led to the development of a new network architecture called the Multichannel Architecture. Key differences between the HF ITF Network and the MCA are that the latter allows any transmitter to transmit at any time and allows arbitrary numbers of transmitters and receivers per platform³.

Many of the differences between the HF ITF Network and MCA are the result of the particular applications for which they were initially designed. Originally, the HF ITF Network was designed for use in a Frequency-Hopping (FH) spread spectrum system. In this system, each transmitter was assigned a unique FH code. However, two or more transmissions could interfere with each other. For that reason, forward error correction techniques (FEC) were needed. However, for the spread spectrum application, FEC only works if the cochannel interference levels are small enough. Studies showed that the number of interfering

3. The limiting case of the number of transmitters on a platform is likely to be governed by the tolerable level of co-channel interference at the collocated receivers.

transmissions should be held to five or less. This constraint led to the decision to limit the number of simultaneous transmissions in the HF ITF Network to one per cluster plus the FTDMA transmission. When it became apparent that the required HF spread spectrum hardware would not be available in the near future, interest turned to the application of the HF ITF Network protocols to narrowband systems. The concept was to use multiple, narrowband frequency channels in place of the FH channels. No modifications of the HF ITF Network protocols were needed to adapt them to this “new” application. On the other hand, from the start the MCA was designed as a narrowband system in which the signalling channels are essentially orthogonal (i.e., noninterfering). Under these assumptions, it is no longer necessary to limit the number of simultaneous transmissions, as was done in the HF ITF Network. Of course, allowing transmitters to transmit at any time precludes the use of the MCA for spread spectrum systems where cochannel interference is a limiting factor.

2.4.1 Network Reorganization

Like the HF ITF Network, the MCA organizes the network into clusters and obtains an intermediate BN using the Linked Cluster Algorithm. Additional transmission frames, beyond the two required by the Linked Cluster Algorithm, are then used by the MCA to obtain the final BN, which better approximates an MBN. These two steps are contained in pseudocode appearing in the Appendix. It is this final BN that performs all of the routing in the MCA system. An important difference in the MCA is the absence of a dedicated FTDMA schedule (and receiver) for handling the control messages for reorganization. Instead, the reorganization messages can periodically use slots in the variable schedules for sending these control messages.

2.4.2 Transmitter and Receiver Scheduling

A significant difference between the HF ITF Network and MCA is the way in which transmissions are scheduled. The HF ITF Network uses cluster schedules in which each clusterhead hands out a portion (or all) of its cluster schedule capacity to neighboring nodes. Each nonclusterhead node then announces its transmission schedule. This allows the receivers of neighboring nodes to schedule appropriately. Thus, the scheduling is transmission driven.

The MCA takes advantage of the fact that in a narrowband, multichannel system, the factor that limits transmissions is the receiver’s ability to listen. Therefore, in the MCA, after the relays are determined, each relay computes its receiver schedule(s) and announces them. Each node schedules its receivers to give equal time to each neighboring node on the backbone and some time to listen to neighboring ordinary nodes. The receiver schedules are used to decide which message is to be transmitted at each transmission opportunity. If the number of neighbors exceeds the number of receivers, multiple transmissions of the same message may be necessary. This is in marked contrast with both the HF ITF Network and IHAMA in which all neighboring nodes always listen to the transmission. However, because any node can transmit all of the time in the MCA, the extra transmissions do not adversely affect throughput performance.

2.4.3 Estimating Load Capacity

Fully connected networks in IHAMA and MCA require no relaying. For MCA, this leads to the pleasant result that

$$L'_{\max} = n_r \quad (\text{fully connected MCA network}).$$

A star network is not fully connected, but it does contain one or more nodes connected to all others in the network. These k fully connected nodes can be used as relays. With n_r receivers per node, two cases must be considered, $n_r \leq k$ and $k < n_r$. For the former case, the first n_r fully connected nodes can be used as relays. The total relay traffic needs of the remaining $(N - n_r)$ nodes can be equally divided among these relay nodes. Thus, each relay node needs to transmit data at the rate $((N - n_r)(l/n_r) + l)$. Equating this transmission rate to C , we can solve for the normalized load capacity to obtain

$$L'_{\max} = n_r \quad (\text{star MCA network with } n_r \leq k).$$

If $k < n_r$, then the relay traffic can be divided among k relays. In that case, each relay node needs to transmit data at the rate $((N - k)(l/k) + l)$. Equating this rate to C , we can obtain the normalized load capacity

$$L'_{\max} = k \quad (\text{star MCA network with } k < n_r).$$

It is straightforward to show that the load capacity of an MCA multihop network for the case where the number of receivers per node n_r always exceeds the number of relay nodes to which any node is directly connected h_{\max} is given by

$$L'_{\max} = 1 \quad (\text{multihop MCA network with } n_r > h_{\max}).$$

For situations in which the number of receivers is $n_r \leq h_{\max}$, the determination of the load capacity is much more complex. The rate at which relay node i can empty its input buffers is dependent on how many relay neighbors node i has (X_i), the probability that neighboring relay j has a receiver tuned to node i ($F_{i,j}$), and the percentage of the total system load received from nonrelay nodes by node j (P_j). $F_{i,j}$ is equal to $\min(1, n_r / (X_j + P_j))$ since node j 's receivers must divide their time between listening to adjacent relay nodes and to the nonrelay nodes that it must service. If each node is generating the same traffic load, then the percentage of traffic generated by each node is simply $1/N$. We assume that a nonrelay node distributes this traffic uniformly over the relay nodes to which it is connected. As a result, P_j is obtained from the equation

$$P_j = 1/N \sum_k 1/X_k,$$

where the sum is performed over all nonrelay neighbors of node j .

To evaluate the average performance of a relay node under the MCA, a queueing simulation was constructed to evaluate the number of slots needed to empty a queue of 10,000 messages as a function of X_i , F'_i , and P_i , where $F'_i = \min(F_{i,j})$. The reciprocal of the number of transmission periods needed for each message was used as the performance of the relay node. These results were computed for $1 \leq X_i \leq 6$, $0 \leq F'_i \leq 1$, and $0 \leq P_i \leq 1$, resulting in a table of performance results. These tables were used to look up the performance of each relay node in the simulations.

After all of the relay node performance estimates were computed, the minimum performance was used to measure the throughput performance of the system. This follows from the fact that we were modelling a system using only broadcast traffic; therefore, all traffic used every relay. Thus, the minimum capacity relay limited the system throughput.

3. NETWORK PERFORMANCE RESULTS

To estimate the performance of MCA and IHAMA under a variety of conditions, a program was developed to generate random networks. For each network, the program computed its connectivity, computed a backbone, performed transmitter (IHAMA) or receiver (MCA) scheduling, and estimated the load capacity of the network. The latter was averaged across many generated networks, resulting in performance curves.

3.1 Random Network Generation

In our simulator, the parameters that control network topology are the number of nodes in the network (network size), the normalized communication range, and the random number for positioning the nodes. With the network size and the normalized communication range defined, a network is generated by randomly positioning each node in a unit square. After all nodes are positioned, a connectivity table is computed by determining whether the distance between node pairs is less than the normalized communication range.

The simulations examined network sizes from 12 to 50 nodes and normalized communication ranges from 0.25 to 1.4 (multihop to fully connected). The performance of each network was examined using the techniques described in Sections 2.2 and 2.4.3. For each combination of network size and normalized communication range, the load capacities of 1000 randomly generated networks were computed and averaged together. The following sections present some of these performance results. For clarity only the average performance is shown, however, the variance was found to be relatively small.

Due to the desire to keep the results general and independent of equipment performance issues, neither MCA nor IHAMA results include any estimate of overhead. Overhead was not addressed because it depends on implementation details, which are beyond the scope of this report. The overhead of IHAMA and MCA are thought to be comparable.

3.2 Load Capacity

Figures 4 and 5 show the Normalized Load Capacities of the different MCA configurations and single-channel Idealized HAMA (IHAMA/SC) for 12-node and 50-node networks, respectively. The abscissa can be divided into three distinct regions depending on the value of the Normalized Communication Range ρ' : multihop networks ($\rho' < 0.65$), star networks ($0.65 < \rho' < 1.2$), and fully connected networks ($1.2 < \rho'$).

Many of the features exhibited in Figs. 4 and 5 are readily recognized given the performance equations for IHAMA (see Section 2.2) and MCA (see Section 2.4.3). For example, as noted in Section 2.4.3, the Normalized Load Capacity of a fully connected MCA network is given by $L'_{\max} = n_r$. This accounts for the shapes of the curves for MCA networks shown in Figs. 4 and 5 over the range $1.2 < \rho'$. Actually, the results show that the range over which $L'_{\max} \approx n_r$ extends to $1.0 < \rho'$. This is because the range $1.0 < \rho' < 1.2$ corresponds to star networks with $n_r \leq k$, and we know that $L'_{\max} = n_r$ under these conditions. These relationships result in the steeper curves for the 50 node networks as compared to 12 node networks, since there is a higher probability of a large number of fully connected nodes in a larger network.

When ρ' becomes increasingly smaller than 1.0, the number of fully connected nodes in the star networks approaches 1. As this occurs, L'_{\max} decreases from its maximum value n_r and asymptotically approaches its multihop value ($\rho' < 0.65$). For $n_r = 5$, this asymptotic value is approximately 1.0. This implies that, for nearly all networks generated, five receivers per node was enough to guarantee that each relay node could always continuously monitor the transmissions of its neighboring relay nodes.

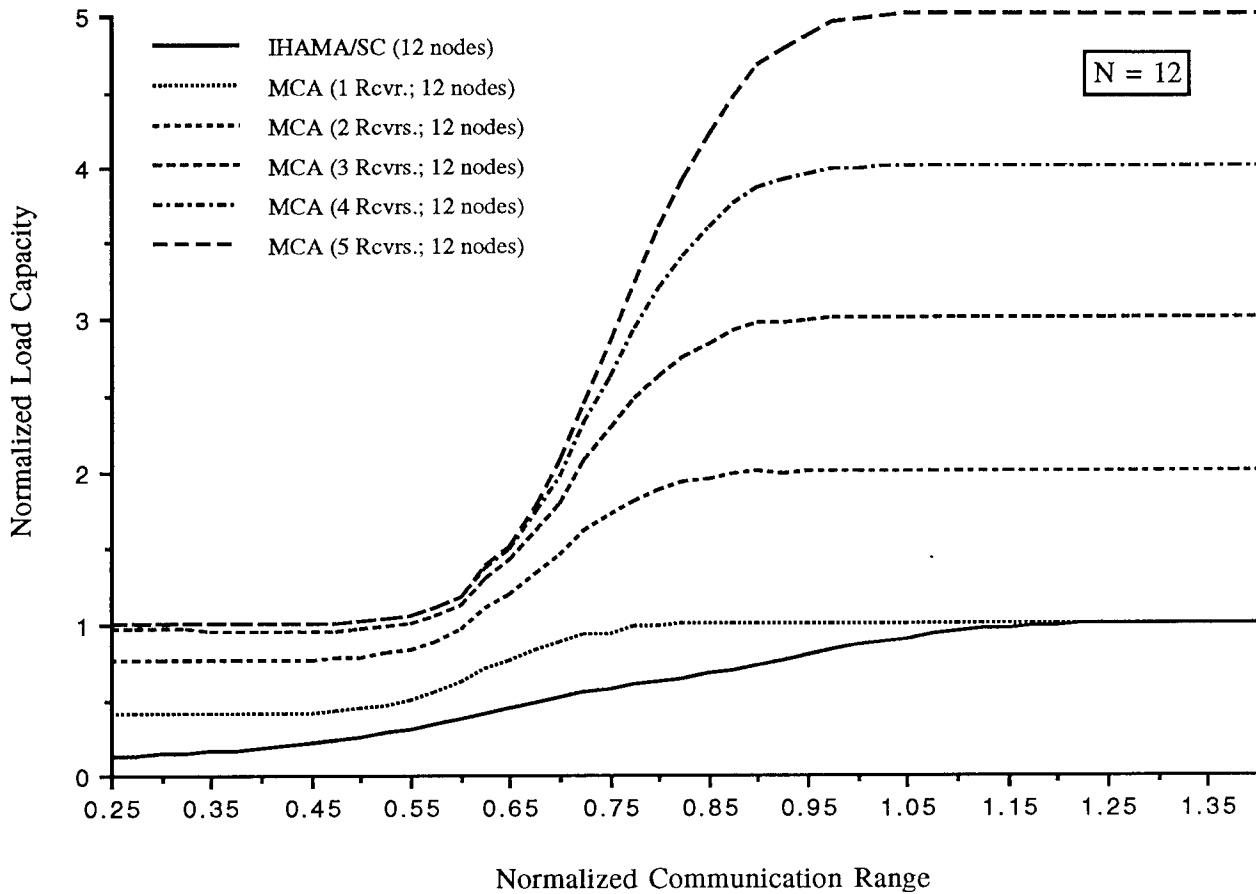


Fig. 4 — Comparison of the normalized load capacities of 12-node IHAMA and MCA networks

For IHAMA networks, the normalized load capacity begins to decrease as soon as full connectivity is lost (i.e., when ρ' is just below the value 1.2). As the Normalized Communication Range decreases below 1.2, full connectivity is lost and star networks are produced. In IHAMA, the Normalized Load Capacity is given by $L'_{\max} = 1 / (2 - k/N)$. When the Normalized Communication Range is reduced so that there are few networks generated that have any fully connected nodes, multihop networks dominate the results. Recall that in the multihop IHAMA networks, the normalized load capacity varies approximately as $1 / (B + 1)$.

In MCA, the performance of the network is only dependent on the performance of the worst case relay connectivity. (The results of the MCA performance have not been solved in closed form, but were generated by a queuing simulation.) However, it is apparent from the results shown in Figs. 4 and 5 that there is little or no dependence of the normalized load capacity on the number of relays required in the multihop regime. On the other hand, IHAMA performance continues to deteriorate as the network becomes sparser.

The most interesting feature in Figs. 4 and 5 is the multihop performance of MCA, which corresponds to Normalized Communication Ranges less than approximately 0.65. As the number of receivers increases, the Normalized Load Capacity of multihop networks rapidly approaches 1.0. This has profound implications for the operation of the networks. A Normalized Load Capacity of 1.0 indicates that all of the transmitters on the backbone are on all of the time and there are enough receivers to listen to every

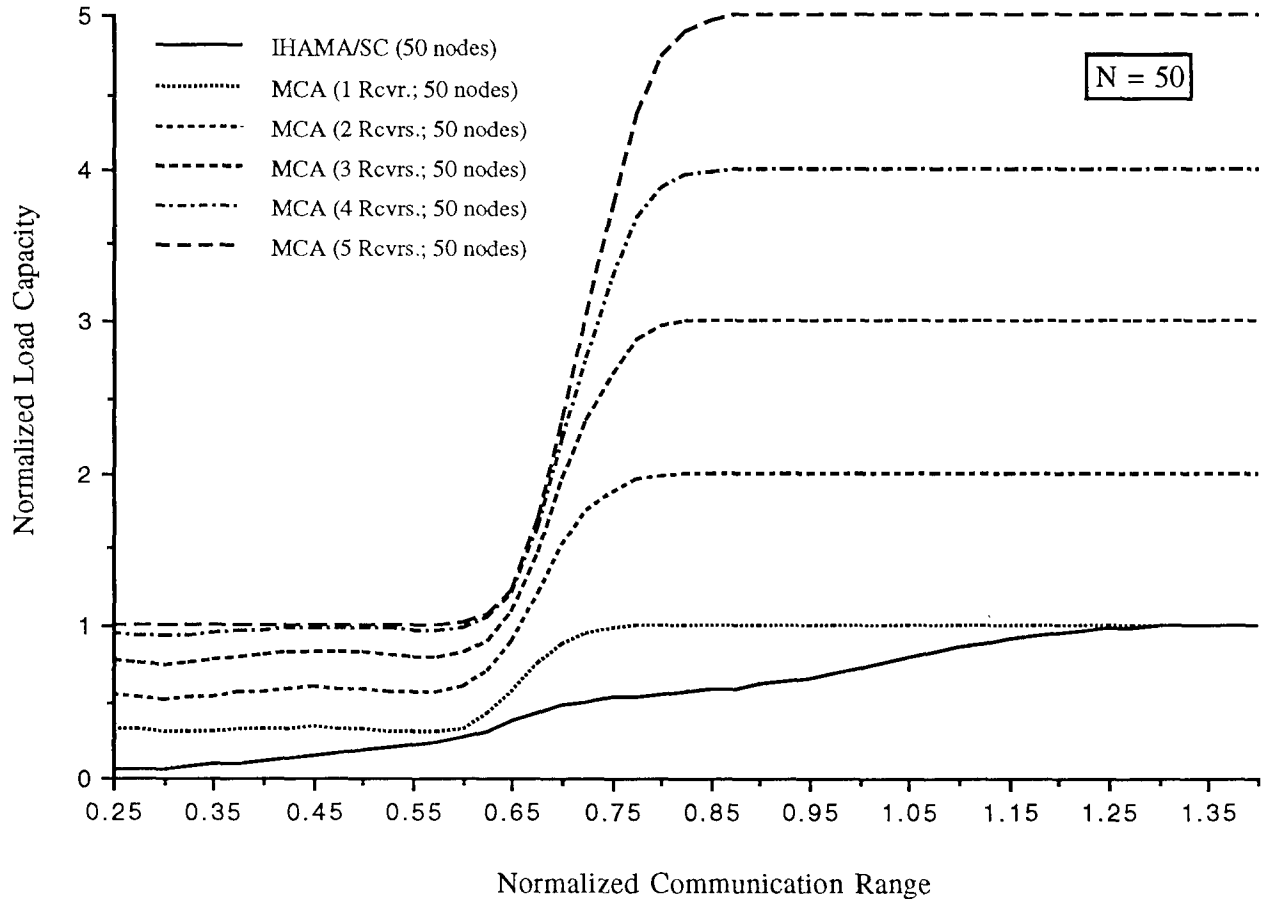


Fig. 5 — Comparison of the normalized load capacities of 50-node IHAMA and MCA networks

transmission. It also permits traffic to be streamed through the network, resulting in very low end-to-end delays. These low delays introduce the possibility of an integrated voice-data network.

3.3 Equipment Normalized Results

Since MCA is generalized for an arbitrary number of receivers, we need a technique for comparing systems with differing equipment requirements. One of the most obvious methods of doing this is by normalizing the performance by the total cost of the system. Owing to the variable costs of hardware, we use a simpler normalization technique. We define the Equipment Normalized Load Capacity L''_{\max} as the Normalized Load Capacity divided by the number of strings of equipment (transmitters and receivers). This assumes that the cost of a receive string is approximately the same as the cost of a transmit string. Thus, if each node has one transmit and one receive string, the Normalized Load Capacity is divided by 2 to obtain the Equipment-Normalized Load Capacity.

Figures 6 and 7 show the Equipment-Normalized Load Capacity of five different MCA configurations and a one-transmitter, one-receiver, Idealized HAMA configuration for 12-node and 50-node networks. The MCA performance curves all use one transmitter, but the number of receivers ranges from one to five as indicated on the legend. These figures are obtained from Figs. 4 and 5 by dividing the MCA results by $n_r + 1$ and dividing the IHAMA results by 2.

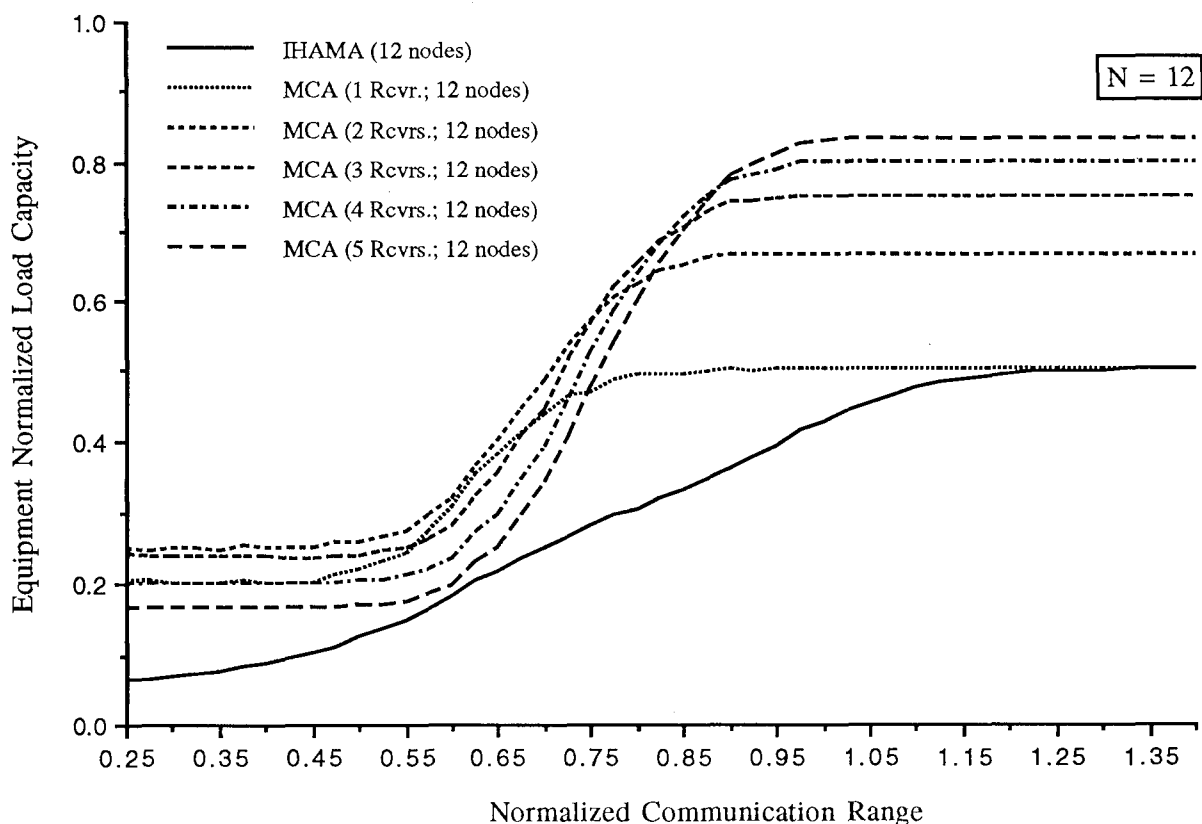


Fig. 6 — Comparison of IHAMA and MCA on a performance-per-equipment basis for a 12-node network

It is clear from Figs. 6 and 7 that for both network sizes all of the MCA configurations outperform IHAMA, independent of the Normalized Communication Range. What is especially striking is the fact that simply allowing the use of multiple frequencies results in improved performance with MCA versus IHAMA even in the one-transmitter, one-receiver case.

An interesting aspect of the MCA multihop performance is the fact that networks with more receivers do not necessarily produce higher ENLCs. For example, for 50 node networks, one transmitter and three receivers appears to maximize the ENLC, while one transmitter and two receivers optimizes the same quantity for 12 nodes. Of course, this is because in very sparse networks, it is inefficient to have more receivers at a node than there are neighboring transmitting nodes.

The ENLC ratio is defined as the ENLC of MCA divided by the ENLC obtained with IHAMA. This ratio gives a clearer picture of the cost benefits of one configuration over another. These ratios are given for 12-node networks in Fig. 8 and for 50 node networks in Fig. 9. MCA ENLC gains over IHAMA of as much as five-to-one are achievable, with gains of two-to-one common. It is also noted that these performance gains are significantly higher for 50 node networks than for 12 node networks.

3.4 Related Issues

We have addressed only the issue of load capacity and ENLC for comparing the MCA and IHAMA architectures. However, these performance results and the structure of the systems give insight into other important issues such as handling voice traffic, frequency usage, end-to-end delays, operational security,

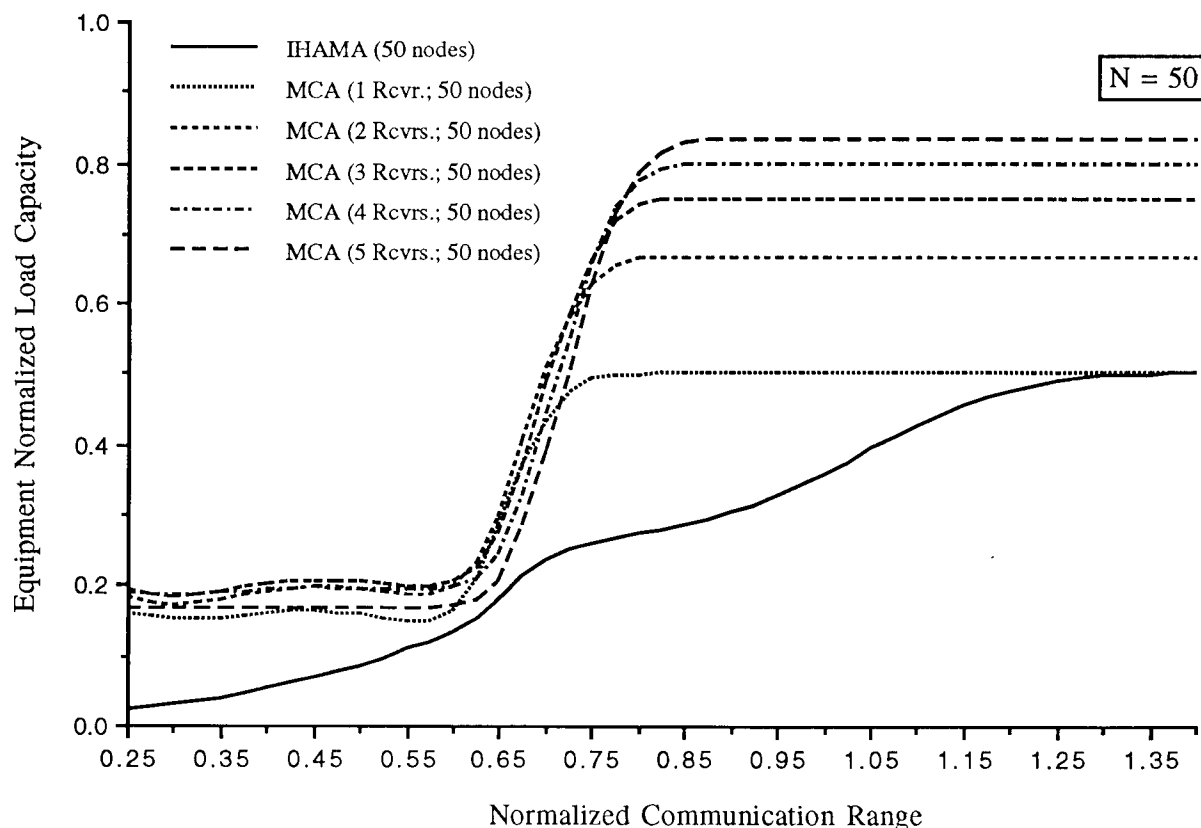


Fig. 7 — Comparison of IHAMA and MCA on a performance-per-equipment basis for a 50-node network

and robustness to jamming. In this section, these issues are examined by considering some of the theoretical limitations of HAMA and MCA. We also examine some of the issues that relate to the implementation of MCA and IHAMA systems.

3.4.1 Virtual Circuits and Voice

Two related classes of service that are important for Navy intratask force communications are virtual circuit connections and voice service. A virtual circuit connection can be defined as a virtual path providing low delay and a specified bandwidth of data between a source and any number of destinations. Due to the high-throughput, low-delay requirements of voice, voice service requires the use of a virtual circuit for implementation.

The implementation of a virtual circuit in IHAMA is limited by several factors. If a single IHAMA system is used and relaying is necessary, the receivers must synchronize with the transmitter on every slot. This requirement means that the minimum delay for each relay node is one slot. In addition, since the normalized load capacity of an IHAMA system with only one (nonrelay) node sourcing traffic is $1/(B+1)$, each relay gets only every $(B+1)$ th slot. This results in a minimum delay of $(B+1)$ slots if the assignments are set up in the “proper” order. For HF systems, the slot size is typically more than 0.5 s for efficiency reasons. This limits voice circuits to two-hop links (for a 1.0 s delay). Alternatively, if a multi-frequency IHAMA system could be constructed that used only a single backbone network, then with $(B+1)$ IHAMA systems, the traffic source and each relay transmitter could be on all of the time, and voice traffic could be streamed through the system with very low delay.

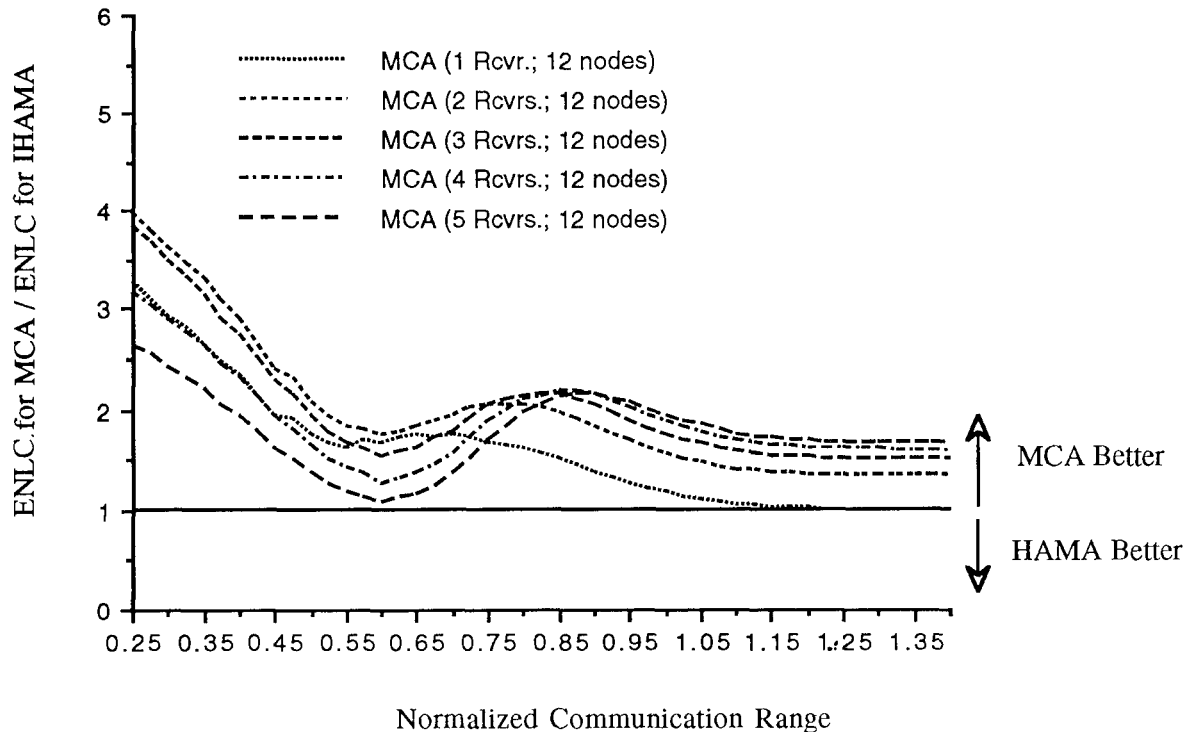


Fig. 8 — Equipment Normalized Performance Ratio Curves for a 12-node network

MCA has a much more effective technique for creating and maintaining virtual connections. Since each node in the backbone network has a unique frequency, all of them can transmit simultaneously. To set up a virtual circuit, all that is required is that each relay node have a receiver tuned “upstream” to listen to the transmissions. This virtual connection is set up using a simple control message sequence that directs each relay node to tune one of its receivers upstream. If a bidirectional link is desired, nodes must be equipped with two receivers: one looking upstream, the other downstream. Due to the fact that the transmitters and receivers are constantly active when implementing a virtual channel, the delay rates can be as low as tens of milliseconds per hop.

3.4.2 Delays

To adequately compare IHAMA and MCA systems, we should consider both the load capacity and delay of these systems. We have examined the load capacities of both IHAMA and MCA in detail. Delay cannot be characterized with the analyses and simulations we performed. However, under limited conditions, the average delays at each relay node can be approximated. These node-by-node approximations do not tell the whole story, but they do give insight into the relative magnitudes of delays between MCA and IHAMA.

The delays of a three-transmitter, three-receiver IHAMA system are compared with that of a one-transmitter, five-receiver MCA system in the absence of queuing. We further idealize the multichannel IHAMA system by assuming that connectivities are the same for each IHAMA channel. This permits the IHAMA system to easily identify a single-backbone network for relaying. The delays that we shall compute for the single-backbone, multichannel IHAMA system are less than those obtained if each IHAMA channel had its own backbone network. Our comparison is “fair” in that both the MCA and IHAMA systems require the same number of equipment suites.

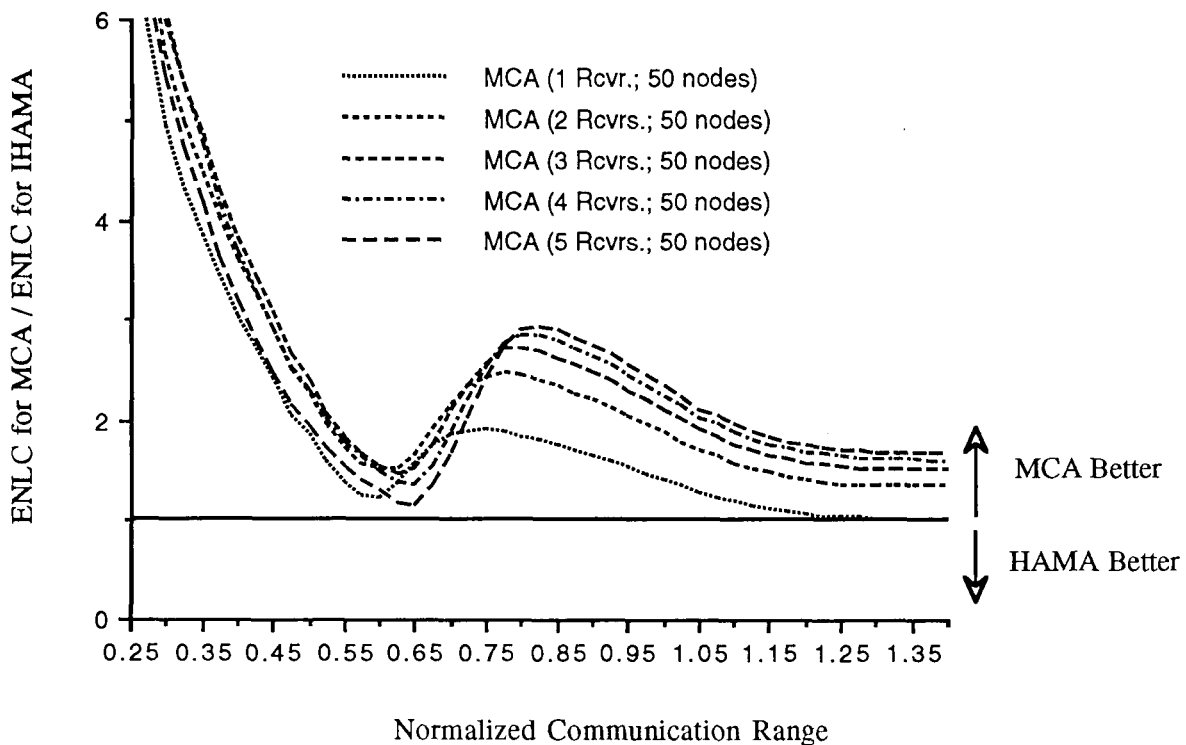


Fig. 9 — Equipment Normalized Performance Ratio Curves for a 50-node network

For fully connected networks, both example IHAMA and MCA systems experience a delay (i.e., the time the first bit is transmitted until the last bit is received) of one packet transmission duration T_p , since all nodes receive the traffic immediately.

If the network is a star network, the traffic transmitted by each relay node is $(N - k)(1/k) + 1 = Nl/k$, and the traffic transmitted by each nonrelay node is l . Therefore, for the example multifrequency IHAMA network, the fraction of the total capacity of $3C$ that is used by the relay nodes is $3C / (2 - k/N) > C$. Thus, for any time slot, a transmitter will be free and a minimum delay of $2T_p$ will be experienced by relayed traffic, one for the original transmission and one for the relay⁴. For the example MCA network, the relays are constantly active, resulting in the same delay.

Multihop network topologies for the example MCA system experience a minimum delay of T_p per relay node traversed since each relay constantly transmits. This results in an end-to-end delay equal to the maximum network diameter (in number of hops) times T_p . In the example multifrequency IHAMA system, each relay only transmits $3 / (B + 1 - B/N)$ of the time. If B is greater than 2, each relay will add a delay averaging more than T_p . Thus, the example MCA system has the same or lower delay than the equivalently equipped example multifrequency IHAMA system for any network topology.

4. We assume that a node does not begin to relay a packet until the packet has been received in its entirety.

3.4.3 Frequency Usage

It might be argued that the performance gains of the MCA over IHAMA are a result of the fact that the MCA uses many frequencies (ideally one frequency per node). To see that this is not the case, we consider the theoretical limits to MCA performance that result from limiting the number of frequencies available to MCA. A minimum frequency requirement can be derived and can be compared to the required number of IHAMA systems needed to perform at the same throughput.

In an MCA system with B relay nodes, the greatest number of frequencies that must be active at any time to support unidirectional virtual circuits is $B + 1$. Each relay node can transmit at any time and only one nonrelay node can enter traffic into the backbone network at a time⁵. Thus, an MCA system can be limited to $B + 1$ frequencies with no degradation. If we assume an MCA system with one transmitter and five receivers, the normalized load capacity of all multihop networks is almost exactly 1.0. To get the same or better performance from an IHAMA system, $B + 1$ transceiver pairs and $B + 1$ frequencies would have to be used. Thus, a one-transmitter, five-receiver MCA system has the potential to use frequencies as efficiently as IHAMA.

To compare MCA and IHAMA performance for the case where there are not enough frequencies to permit relay nodes to have separate frequencies, we make the same assumption that we made for the multi-frequency IHAMA system. Namely, we idealize the system by assuming that connectivities are the same for each frequency channel. This enables the MCA system to easily identify a single-backbone network for relaying.

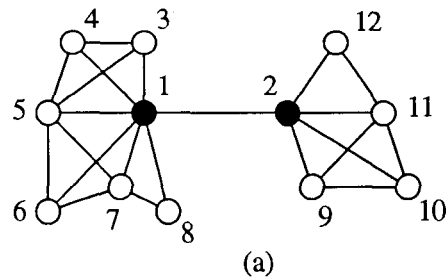
If the number of frequencies available to a five-receiver MCA system is limited to a fixed number F , a transmission schedule can be constructed for multihop networks that gives a normalized load capacity of $F / (B + 1)$ for the case $F \leq B$; otherwise, the normalized load capacity is almost exactly 1.0 for the case $F > B$. Figure 10 shows how the transmissions are scheduled to achieve this performance. If the number of frequencies is reduced to 1, a normalized load capacity and schedule identical to that for a single-channel IHAMA will result! This indicates that, in terms of theoretical limits on the load capacity, IHAMA is a degenerate case of the MCA for one receiver, one transmitter, and one frequency.

3.4.4 Operational Security and Robustness to Jamming

Another comparison to be made between MCA and IHAMA is their resistance to jamming and traffic analysis. Using IHAMA, only one transmitter is on at any time and only one frequency is used. An interceptor of this signal can infer by the amount of time that a node is on whether the node is an ordinary node or a relay and how much traffic each ordinary node enters into the network. The opponent can then plan a jamming response to disconnect the network by jamming a critical relay at the right time. The jammer can thus optimize the use of power in two ways: by restricting the frequency that the jammer is used on and restricting the jamming time.

The MCA allows every node to transmit all of the time on its unique frequency. If the node has nothing to transmit, a dummy message can be sent. Since the messages are likely to be encrypted, the interceptor cannot detect the difference between a dummy message and real traffic. Therefore, with all of the nodes transmitting at all times on different frequencies, the interceptor can gain no knowledge of the network traffic pattern or structure. Without this knowledge, the only jamming technique the interceptor can be sure

5. This assumes that a virtual circuit consumes nearly all of the transmission capacity of a relay node. In practice, this may not be the case, which leads to the possibility of multiple virtual circuits and/or voice/data integration.



Slot #	Node 1	Node2	Source
1	f1	f2	f3
2	f1	f2	f3
3	f1	f2	f3
4	f1	f2	f3
5	f1	f2	f3
6	f1	f2	f3
7	f1	f2	f3
8	f1	f2	f3

(b)

Slot #	Node 1	Node 2	Source
1	f1	f2	none
2	none	f1	f2
3	f2	none	f1
4	f1	f2	none
5	none	f1	f2
6	f2	none	f1
7	f1	f2	none
8	none	f1	f2

(c)

Fig. 10 — Methodology for frequency assignment. a) Three-hop network with relay nodes in black. b) Transmission frequency schedule assignment with three frequencies. (Source schedule is distributed evenly to all nonrelays.) c) Schedule assignment with two frequencies. (Source schedule is distributed evenly to all nonrelays.)

will disrupt the network is to jam all frequencies all of the time with sufficiently high power, a task that is generally not possible.

3.4.5 Implementation Issues

This report has focused on the performance of two idealized systems, MCA and IHAMA. Can real implementations approach the performance of these idealized systems? In the next few sections, we examine some of the technical problems that arise in implementing such systems.

3.4.5.1 Frequency Requirements

An idealized MCA network can work with as few as one frequency; however, the preferred mode of operation is to assign a unique transmit frequency to each node. If there are not enough frequencies to permit the latter, then additional protocols must be developed to coordinate frequency usage. Frequencies might be allocated deterministically (statically) or nondeterministically (dynamically). For networks where a significant portion of the traffic is broadcast, which is the case that we have been considering, the goal of the MCA is to allow uninterrupted transmissions by relay nodes on the backbone. It appears that any scheme for dynamically allocating frequencies among all the nodes of a network is only going to be as reli-

able as the communications that is required to support these schemes. In times of stress, intratask force communication links may be highly unreliable; hence, dynamic frequency allocation schemes do not seem to be appropriate. Purely static allocation schemes have the drawback that transmission capacity allocations might not accurately reflect actual needs. A hybrid approach in which a subset of nodes are allocated their own frequencies and the remaining nodes use slot-handoff protocols to share the remaining frequencies seems to be a promising compromise. This would be, in effect, an integrated MCA/IHAMA system.

3.4.5.2 Multiple Receivers

Our results show that near-optimum performance can be obtained for multihop MCA networks with five receivers. Additional protocols must be developed to achieve the results shown for fewer receivers. It should not be difficult to implement efficient protocols for doing receiver scheduling since nodes only need to coordinate with their neighbors to effect the required coordination.

3.4.5.3 Global Knowledge

Unlike MCA, whose performance is only weakly dependent on the number of relay nodes, IHAMA performance degrades rapidly with the increasing number of relays required. Thus, IHAMA needs global connectivity information so as to minimize the number of relays needed. IHAMA also needs global knowledge about the traffic loads so that it can handoff transmission slot opportunities. The implementation of slot handoff among nodes that are not directly connected is a significant technical problem.

4. CONCLUSIONS

We have described the MCA, a mobile radio architecture for Navy intratask force networks that is generalizable to arbitrary numbers of transmitters, receivers, and frequencies. This architecture is formed by a robust reorganization procedure, the Linked Cluster Algorithm. In comparison with an idealized form of IHAMA, a single-channel architecture, it was found that the load capacity of MCA was superior for equivalent cost systems. MCA also outperformed IHAMA in other performance issues such as delay, the ability to handle voice and virtual circuits, and jam resistance. Finally, it was shown that the IHAMA is a degenerate case of the MCA for one transmitter, one receiver, and one frequency.

Given the results presented in this report, it appears that the MCA should be considered strongly as a candidate for use in future Naval intratask force networking for the following reasons:

- Multichannel MCA, using the same one-transmitter/one-receiver configuration as a single-channel IHAMA system can provide better performance.
- The capacity growth with MCA can be effected by adding receivers, a cost-effective growth path to higher capacity.
- MCA hardware can be updated one node at a time and maintain operability throughout the upgrade.
- It takes advantage in hardware, with its one-transmitter/multiple-receiver configuration, of the fact that, in a Fleet intratask force system, ships and aircraft will listen more than transmit.
- The insensitivity of MCA throughput performance to the sparseness of networks opens up the 10 to 30 MHz HF and UHF bands for Naval intratask force networking.
- The MCA can handle voice.

- The high throughput and low delay makes integrated voice-data networking feasible.
- MCA can be combined with slot handoff schemes when the number of frequencies available does not permit the allocation of a unique frequency to each MCA node.

Perhaps the most powerful feature of the MCA is the potential to support virtual circuits for point-to-point traffic and broadcasting from one node to all others. This feature is needed for time-critical services such as voice. It may also prove to be the preferred method to send NTDS and some of the other data traffic.

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APPENDIX

Approximating the Minimum Backbone Network

As indicated in Section 2.2, the load capacity of an IHAMA network is heavily dependent on the number of relay nodes B . By minimizing the number of required relay nodes used for a network, the performance of IHAMA can be optimized. Any valid set of relays must fulfill two criteria: every node in the network must be connected to at least one relay and the relays must form a connected subnet. A valid set of relays with the minimum number of relays is termed a Minimum Backbone Network (MBN).

USING GLOBAL KNOWLEDGE

The MBN can be determined using global knowledge of the network connectivity. Unfortunately, the exact solution of the MBN for large networks is computationally infeasible. However, for comparing the MCA and IHAMA architectures, it is not necessary to compute the MBN but rather to compute a common backbone network (BN) that is used by both architectures. When global connectivity information is known, the network can be represented as an undirected graph. The vertices and edges of the graph represent the nodes and bidirectional links of the network, respectively.

Figure A1 gives a heuristic for approximating the MBN of an undirected graph. In line 1, the set of clusterhead nodes is determined as follows. Each node has three attributes called `node_id`, `own_head`, and `label`. The nodes are first numbered (`node_id` is set) from 1 to N ; `own_head` is initialized to 0; and `label` is set to UNLABELED. Then node 1 is labeled a CLUSTERHEAD and its `own_head` is set to 1. All nodes connected to the new clusterhead are temporarily labeled as IN_A_CLUSTER, and their `own_head` is also set to 1. The lowest numbered node that is not labeled CLUSTERHEAD or IN_A_CLUSTER becomes the next CLUSTERHEAD. The new clusterhead sets `own_head` to its own `node_id`. UNLABELED nodes connected to the new clusterhead are labeled as IN_A_CLUSTER, and the `own_head` of each is also set to the `node_id` of the new clusterhead. The process is repeated until all nodes are labeled as either CLUSTERHEAD or IN_A_CLUSTER.

In line 2, nodes that were temporarily labeled as IN_A_CLUSTER are relabeled as BOUNDARY_NODE if a) the node has a neighbor with a different `own_head` than the node's `own_head` and b) the neighbor's `own_head` is not connected to the node's `own_head`. In line 3, all nodes still labeled IN_A_CLUSTER are relabeled TERMINATOR_NODE.

After initializing the BN to the empty set in line 4, lines 5 through 8 implement a greedy algorithm in which the non-TERMINATOR_NODES that will add the most new neighbors to the BN are chosen as new members of the BN. This is done until the BN is connected to every node in the network. The next and most computationally intensive task (lines 9 through 17) is to make sure that the BN is a connected subnetwork. This is accomplished by doing a shortest-path computation (Dijkstra's Algorithm) from every node

```

1  find set of clusterhead nodes
2  label nodes connecting CLUSTERHEADs BOUNDARY_NODE
3  all other non CLUSTERHEAD nodes labeled TERMINATOR_NODE
4  initialize BN to the empty set
5  while BN is not connected to all nodes
6      find non TERMINATOR_NODE that adds
7          maximal neighbors to BN
8      add node to BN
9  weight each link (i,j) as follows:
10     case (i,j) unconnected label Infinity
11     case i or j is TERMINATOR_NODE label Infinity
12     case i and j on BN label 1
13     case i on BN or j on BN label 10
14     otherwise label 100
15  find shortest paths across network
16  use paths generated to connect BN
17  add nodes used to connect to BN

```

Fig. A1 — Algorithm to compute a backbone network using global knowledge

chosen as part of the BN. Other links are labeled such that a minimal number of nodes are added to the BN. Links that add no nodes cost 1, one node costs 10, and 2 nodes cost 100. Finding the shortest path using these link costs ensures that a nearly minimal number of nodes will be added to provide connectivity along the BN. The added nodes are discovered in line 17 and added to the BN.

The backbone networks generated by this method appear to be sensitive to the way in which the nodes are numbered. If the method is replicated several times by using different sets of random numberings of the nodes, the smallest backbone network appears to be very close to the MBNs derived by careful visual inspection. Panel (b) of Figs. A3 through A5 show some examples of networks and BNs computed using global knowledge. These figures illustrate how ρ' relates to topology and compare the BNs obtained with global and local knowledge. As can be seen in panel (a) of Figs. A3 through A5, the local-knowledge BN provides a larger backbone than does the global-knowledge algorithm. This is unavoidable because of the limitation of the information available.

USING LOCAL KNOWLEDGE

The potentially rapid topology change in an intratask force network may necessitate using only local information for structuring. This will typically result in developing backbone networks that are far from optimal. However, the redundancy in the backbone can be used to advantage to provide more reliable message delivery. This section describes the formation of a backbone network by using a distributed algorithm and local topology knowledge.

In the distributed formation of the BN, both the communication sequence and the algorithm must be illustrated. In the algorithm that we describe, topology information need only be relayed once. This is known as two-hop information, since the traffic comes from nodes at most two transmissions (hops) away.

The approach that was taken starts with breaking the network up into clusters, as in the global-knowledge case. However, the information and structure derived from clustering is used more extensively by the local-knowledge algorithm. With only two-hop knowledge, the only decision that a cluster can make about its connections to neighbors is that it must choose BN nodes such that it has a connection to all clusters that

have nodes within two hops. This is actually looking three hops away, but the effect is achieved by letting gateway nodes make some of the decisions.

Due to the integrated behavior of the communications and computations, we list the processes together in Fig. A2. Note that all communications indicated are local and do not require routing. In each frame, we require that nodes transmit in sequence, according to their node number.

```

Frame 1:
    Probe to learn connectivity information
Frame 2:
    Determine clusterhead status
    Complete ACK/NAK of probes and
        announce connectivity and clusterhead status
End of Frame 2:
    Compute gateways
Frame 3:
    Report clusterhead connections
End of Frame 3:
    For each clusterhead
        Choose min set of nodes to connect to all
            adjacent clusterheads
Frame 4:
    Clusterheads report BN connections
    Boundary nodes report 2-hop clusterhead connections
    Connect to unique 2-hop gateways
Frame 5:
    Determine 2-hop gateway connections
    Broadcast 2-hop gateway connections

```

Fig. A2 — Pseudocode for the distributed process to form a backbone network with local knowledge

The probe transmissions and the ACK/NAK of these probes in frames 1 and 2 are used by each node to discover to which nodes it is bidirectionally connected by direct links. This is done in frame 1 by sending a message at each node with a bit set to 1 for each node heard previously and a bit set to 0 for those nodes not heard from. Since each node can only have heard from the nodes on the schedule preceding it, the i th node need only send $i - 1$ bits. However, at the end of the first transmission, the full bidirectional connectivity has not been established. Thus, the transmission in frame 2 is used to complete the ACK/NAK with each node i sending the remaining $N - i$ bits describing the connectivity. In addition, in frame 2 each node sends an additional bit, which is called the "clusterhead bit." This is used to indicate whether a node is a clusterhead. The rule for setting this bit is simple: if no neighbor (i.e., node to which a bidirectional link exists) has become a clusterhead, set the clusterhead bit, label the node as a clusterhead, and add it to the BN.

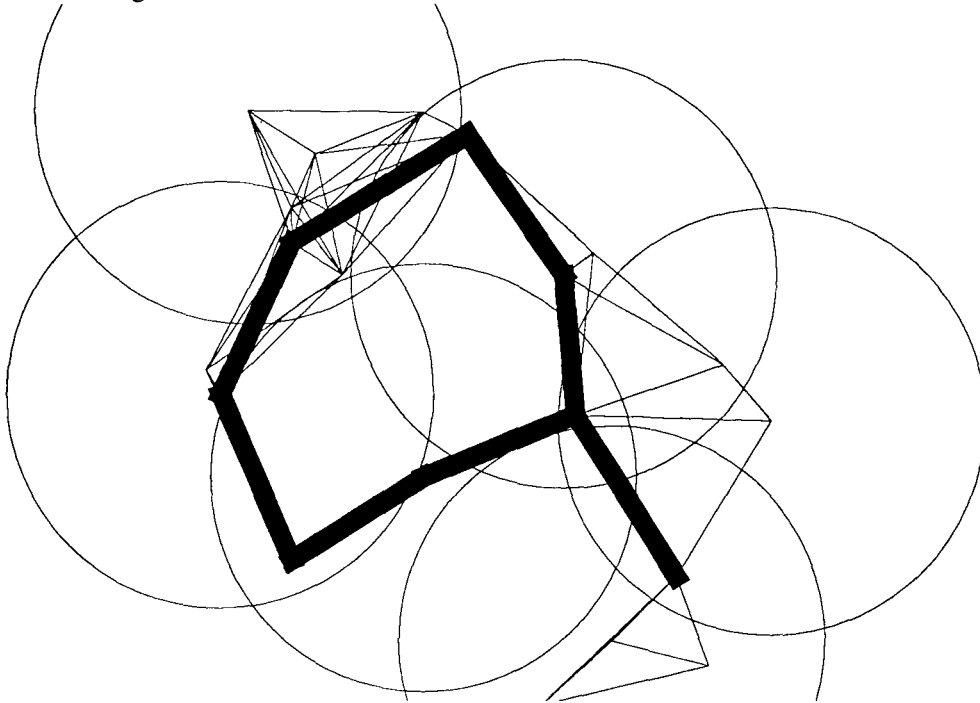
Once the clusterheads are announced (at the end of frame 2), the gateway nodes can be computed as those connecting two clusterheads. This linkage can connect either overlapping (i.e., gateway is connected to both clusterheads) or adjacent, nonoverlapping (i.e., gateway is connected to one of the clusterheads and also to another node that is connected to the second clusterhead). In the latter case, the clusterheads are linked by a pair of gateways.

Transmissions in frame 3 are used by all nonclusterhead nodes to report the clusterheads to which they are attached. With this information, each clusterhead chooses (at the end of frame 3) a minimal set of gateways that are connected to all adjacent clusterheads and labels them members of the BN.

During transmissions in frame 4, these clusterhead connections to BN nodes, along with a list of all two-hop clusterheads, are then announced by each clusterhead. Once this information is passed (at the end of frame 4), it is possible to form the two-hop gateway pairs. A node becomes one-half of a two-hop gateway pair when it determines that the addition of the gateway will provide connections with one or more clusters not already two-hop connected to any neighboring clusterheads. When a decision is made to form a two-hop gateway, the node broadcasts (in frame 5) the connection(s) it has made by using a list of bits. The nodes that it has chosen to connect to also become two-hop gateways upon receiving this transmission. At the end of transmissions in frame 5, all of the two-hop gateways' transmissions will have been completed, and the backbone will be fully formed. It is guaranteed that, in the absence of errors, the BN will provide at least one path from every node to every other node in the network.

One additional step can be added to decrease the size of the BN. Any clusterhead may be eliminated from the backbone if the backbone nodes it is connected to form a connected subgraph that is connected to all other nodes in the cluster. This extra step requires no extra communication since the data is already present at the clusterhead.

(a) Local Knowledge



b) Global Knowledge

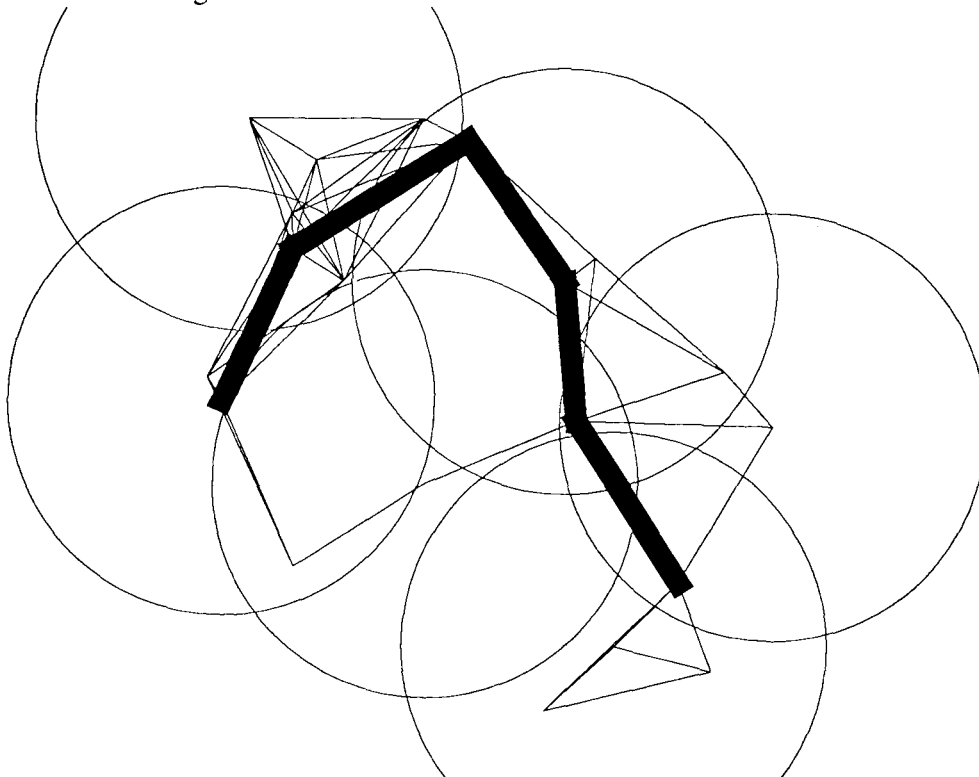
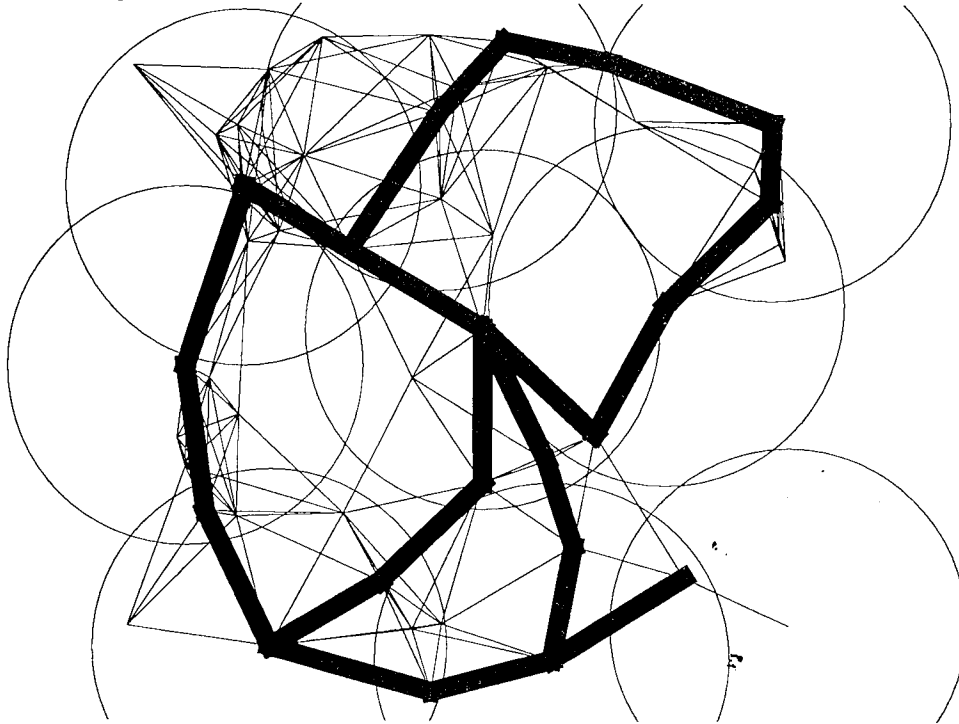


Fig. A3 — Example backbone for a 20-node network with $\rho' = 0.3$
obtained with: a) local knowledge and b) global knowledge

(a) Local Knowledge



(b) Global Knowledge

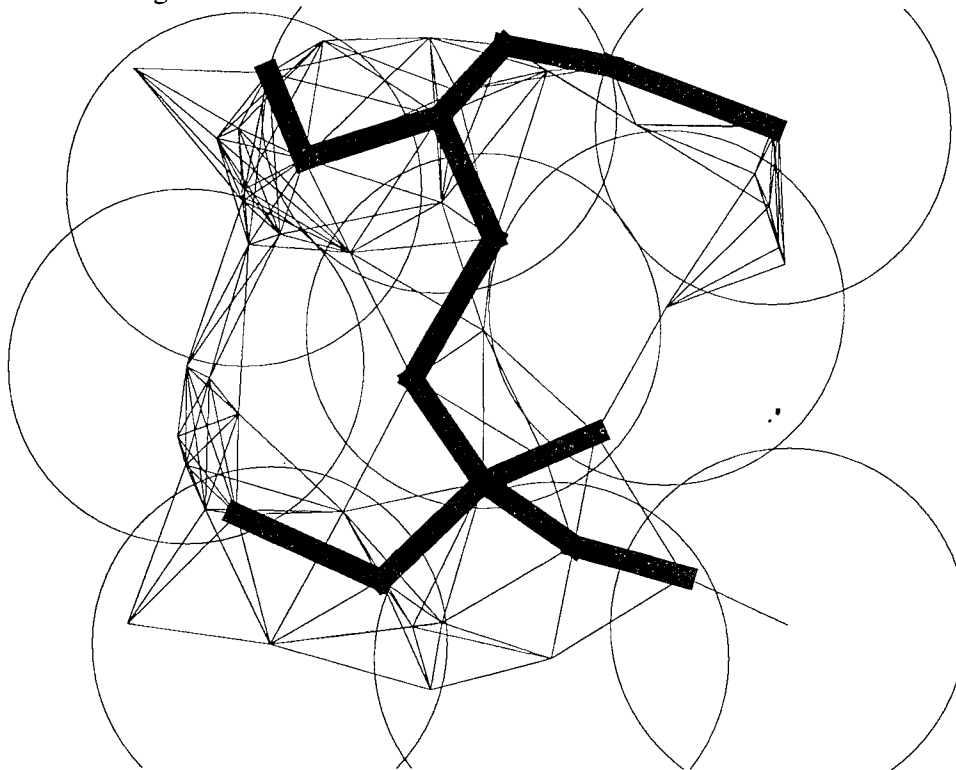
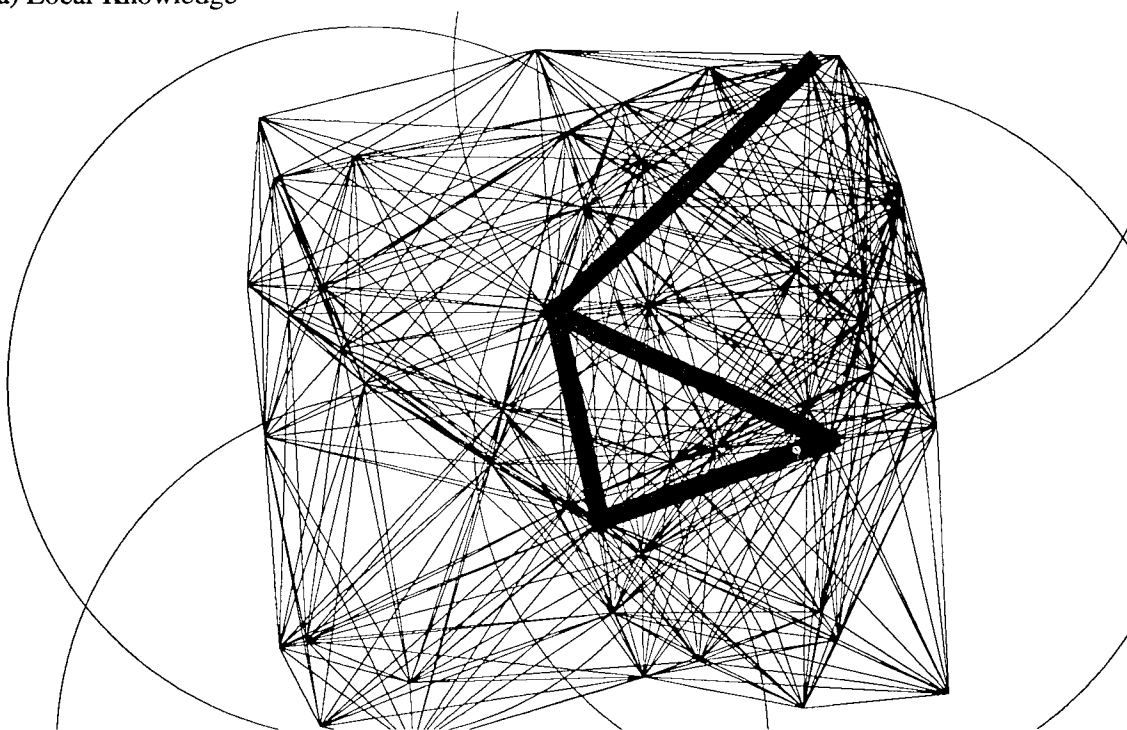


Fig. A4 — Example backbone for a 50-node network with $p' = 0.25$
obtained with: a) local knowledge and b) global knowledge

(a) Local Knowledge



(b) Global Knowledge

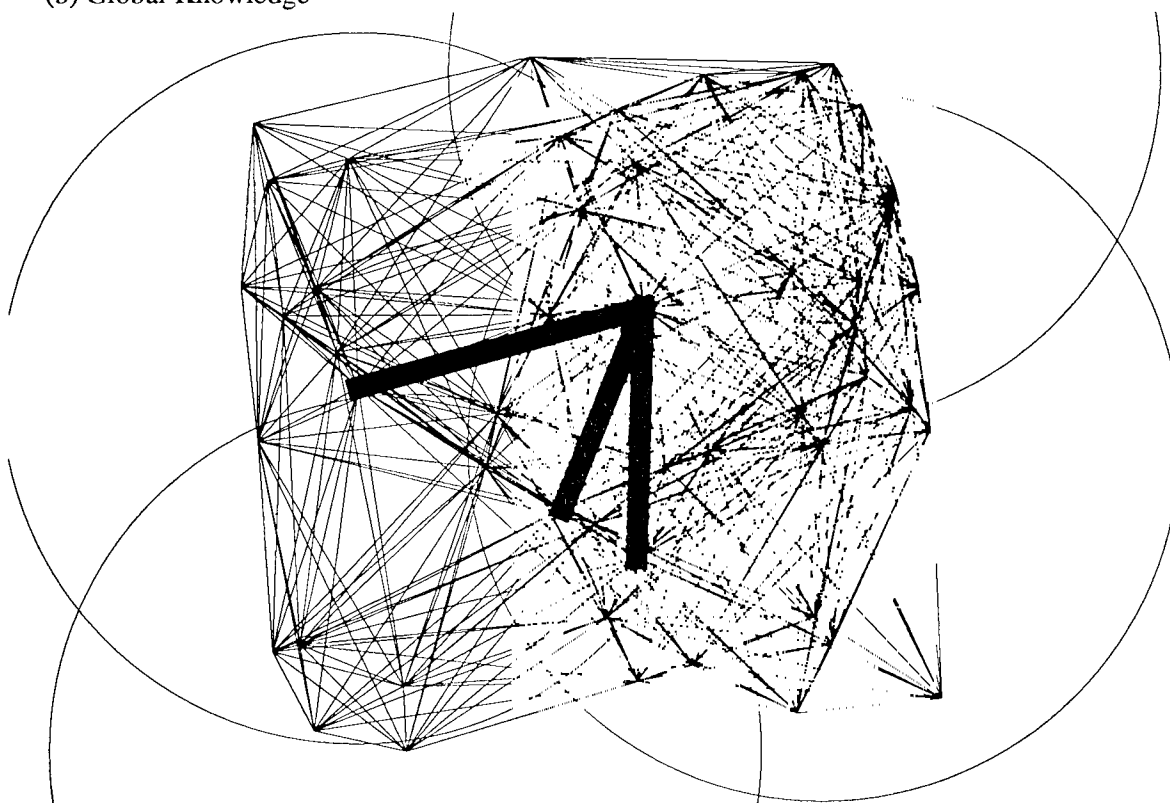


Fig. A5 — Example backbone for a 50-node network with $\rho' = 0.5$ obtained with: a) local knowledge and b) global knowledge

